Appendix D
Excess Effluent Stream Flow Infiltration Routing Analysis Methodology

A stream flow routing analysis was conducted to estimate flow in Greenbush Draw and potential recharge to the basin fill aquifer between the planned effluent outfall location and the Arizona Water Company Bisbee Well Field, located approximately 8,000 feet downstream of the outfall. The routing analysis considered a discharge rate of 1.22 million gallons per day (mgd), the maximum monthly effluent flow from the plant, and estimates of the distribution of stream flow losses attributable to infiltration and evapotranspiration. Manning's equation, which provides an empirical approximation of open channel flow, was used to route flows downstream of the planned outfall. Manning's equation is defined as (adapted from Chow, 1988):

$$Q = \frac{1.49}{n} A R^{2/3} S_0^{1/2}$$

where: Q = stream flow rate;
n = Manning's roughness coefficient;
A = cross sectional area;
R = hydraulic radius
S_0 = channel slope.

The hydraulic radius is defined as:

$$R = \frac{A}{P}$$

where: A = cross sectional area; and
P = wetted perimeter.

Typically, channel geometry is specified as an input into Manning's equation. To assess the nature of active channel geometry along Greenbush Draw, Brown and Caldwell personnel conducted field inspections and analyzed aerial imagery utilizing a Geographic Information System (GIS). The geometry was determined to be highly variable within the study area; therefore, Manning's equation was simplified by assuming that the width of flow within the wash will be much greater than the depth of flow. This assumption reduces Manning's equation to the following:

$$Q = \frac{1.49}{n} w d^{5/3} S_0^{1/2}$$

where: w = width of flow; and
d = depth of flow.

An initial flow rate (Q), width of flow (w) in the wash, channel slope (S_0), and roughness coefficient (n) were estimated in order to solve for the depth of stream flow using the reduced form of the Manning's equation. Stream flow rates at the outfall were set equal to 1.22 mgd the maximum monthly amount of effluent available for discharge into Greenbush Draw. Based on the stream channel GIS analysis, the maximum flow width at the outfall was constrained to less than or equal to 27 feet. This value accounts for a reduction in flow width of 25 percent due to the potential impact of channel bars and overbank deposits. Stream channel slope was assumed to be uniform at 0.0047 feet/feet based on the change in surface elevation from the planned outfall location to just beyond the Bisbee Well Field. Manning's roughness coefficient was assumed to be 0.05, a value representative of a winding natural channel (Chow, 1988).

Although evapotranspiration and infiltration are not directly included in Manning's equation, their impacts upon flows in Greenbush Draw were considered. Evapotranspiration also reduces the quantity of water available to downstream reaches and can be divided into two components: a) evaporation from the free surface of the stream and b) evapotranspiration from channel and bank vegetation. Stream evaporation was assumed to occur only from the free surface of the stream body. The stream evaporation rate was held constant for all calculations and was estimated to be 73 inches per year based upon local pan evaporation measurements and a pan coefficient of 0.69 (Savci Environmental Technologies, 1998). From inspection of vegetative patterns from aerial photographs, evapotranspiration along Greenbush Draw was estimated to occur within a 50-foot corridor extending laterally outward from each edge of the stream channel. Evapotranspiration rates were projected to be approximately 0.5 and 1.0 acre-feet/acre in 2004 and 2024, respectively. These values are intended to represent lightly vegetated riparian areas within the San Pedro River corridor, the receiving water body for Greenbush Draw (Lacher, 1994). The higher value for 2024 reflects the growth and development of existing and new vegetated channel reaches after approximately 20 years of assumed discharge.

Infiltration from the streambed was also estimated using single ring infiltrometers and literature values (Lacher, 1996). Infiltration from stream reaches also reduces the quantity of water available for downstream portions of the channel. The rate of infiltration of effluent through the stream channel of Greenbush Draw is dependent upon the vertical hydraulic conductivity of the stream channel deposits. Hydraulic conductivity is dependent upon moisture content and ranges over several orders of magnitude up to a maximum value for saturated conditions. To estimate saturated hydraulic conductivity of the stream-channel deposits, eight single-ring infiltrometer tests were performed in Greenbush Draw on December 12-13, and 17-19, 2002. Test locations extended from the proposed discharge outfall location to the Bisbee Well Field. Literature values from Lacher (1996) coupled with the results of the infiltration testing yielded estimates of long-term vertical infiltration rates ranging between 0.017 and 2.0 ft/day. Infiltration rates generally increased from the Bisbee-Naco Highway Bridge to the Bisbee Well Field and are generally consistent with observed lithology of the stream channel.

Once all necessary inputs were compiled, flow routing calculations for effluent discharged to Greenbush Draw were performed in the following manner using a computer spreadsheet. To estimate stream flow, infiltration, free surface evaporation, and evapotranspiration at specific locations along Greenbush Draw, the stream channel was discretized into 350 segments, or reaches. Each reach was assigned an infiltration rate using a linear interpolation between measured and literature derived infiltration rates (Table 1). The initial input to the flow routing analysis was the volume of effluent to be discharged at the outfall. This value, expressed as a flux term (volume per unit of time), was used as the initial stream flow term (Q) for the modified Manning's equation and was assumed to be representative of flow rates within the first reach of the stream channel adjacent to the outfall. Using the discharge rates and channel widths presented in Table 2 and the slope, and roughness value presented above, the depth of flow within the channel was calculated using the modified Manning's equation. Stream channel surface area was calculated using the reach length and calculated stream width. The estimated surface area was then multiplied by each reach's infiltration and evaporation rates to calculate stream flow losses experienced before the adjacent, downgradient reach. Additionally, losses to evapotranspiration were calculated by multiplying the appropriate evapotranspiration rate by the evapotranspiration area (a 50-foot corridor extending laterally from each edge of the flowing stream multiplied by the length of the stream segment). Evapotranspiration loss was also subtracted from the flow reaching the subsequent segment. Using the newly calculated reduced flow rate and the same depth, slope, and roughness coefficient as before, an updated width of flow was calculated for the downgradient reach again using the reduced form of the Manning's equation. Note that after the initial stream reach, the depth of flow is held constant, while the flow width is allowed to vary. The remainder of the routing process described above was repeated to determine the reduced stream flow and stream width for the remaining stream reaches. These sequential calculations were applied to all 350 discretized segments to evaluate the distribution of stream flow losses and to estimate the percent of surface flow remaining in Greenbush Draw for each of the 350 stream segments from the outfall to the Bisbee Well Field. Lastly, estimated effluent infiltration volumes were summed over an 8,000-foot length of Greenbush Draw to approximate the magnitude of groundwater recharge to the basin fill aquifer in the discharge impact area (DIA).

TABLE #. ESTIMATED LONG-TERM VERTICAL HYDRAULIC CONDUCTIVITY BASED ON INFILTROMETER TESTING

TEST ID	INFILTROMETER RADIUS	INFILTRATION RATE	LATERAL WETTING	VERTICAL WETTING	AVERAGE DEPTH OF WATER	WATER ENTRY VALUE	DOWNWARD FLOW RATE	ESTIMATED LONG-TERM VERTICAL HYDRAULIC CONDUCTIVITY	
	r (ft)	i_n (ft/hr)	x (ft)	L (ft)	z (ft)	h_{we} (ft)	i_w (ft/hr)	k (ft/hr)	k (ft/day)
Ring 0	1.5	0.01	0.75	1.0	0.98	-0.98	0.0052	0.0017	0.042
Ring 1	1.5	0.02	1.8	0.75	0.98	-0.66	0.0034	0.0011	0.025
Ring 2	1.5	0.01	1.7	0.50	0.98	-0.82	0.0032	0.0007	0.017
Ring 3	See Note 1								
Ring 4	1.5	0.13	1.5	2.0	0.93	-0.82	0.033	0.0176	0.423
Ring 5									0.7-1.0[1,2]
Ring 6									1.0-2.0[1,2]
Ring 7									1.0-2.0[1,2]

ft/hr = foot per hour
ft/day = feet per day
1 – Invalid tests caused by antecedent moisture conditions and difficulties measuring vertical and lateral wetting fronts.
2 – Estimated a range of vertical hydraulic conductivity values based on observed coarse-grained lithology, relative magnitude of measurements at locations with finer-grained lithology and values in literature (Lacher, 1996).